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The identification of the optical/IR counterpart of the 15.8-s transient X-ray pulsar XTE J1946+274

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Abstract. We report on the discovery of the optical/IR counterpart of the 15.8 s transient X-ray pulsar XTE J1946+274. We re-analyzed archival *BeppoSAX* observations of XTE J1946+274 obtaining a new refined position (a circle with 22'' radius at 90% confidence level). Based on this new position we carried out optical and infra-red (IR) follow-up observations. Within the new error circle we found a relatively optical faint ($B = 18.6$) IR bright ($H = 12.1$) early type reddened star ($V - R = 1.6$). The optical spectra show strong $H\alpha$ and $H\beta$ emission lines. The IR photometric observations of the field confirm the presence of an IR excess for the $H\alpha$ -emitting star ($K = 11.6$, $J - H = 0.6$) which is likely surrounded by a circumstellar envelope. Spectroscopic and photometric data indicate a B0–1V–IVe spectral-type star located at a distance of 8–10 kpc and confirm the Be-star/X-ray binary nature of XTE J1946+274.

Key words. stars: individual: – XTE J1946+274; GRO J1944+26 – binaries: general – stars: pulsars: general – stars: emission-line, Be – X-rays: stars

1. Introduction

High Mass X-ray Binary systems (HMXRBs) hosting a neutron star (NS) are a class of intrinsically variable and bright X-ray sources whose luminosity is powered by accretion from a massive companion, often a B-emission spectral-type star (BeXRBs; White et al. 1995; Coe 2000).

BeXRBs usually show in the X-ray emission three typical behaviours (sometimes more than one within the same source): (i) bright X-ray transients characterized by giant outburst with luminosity up to $L_x = 10^{38}$ erg s⁻¹ (Type II; Stella et al. 1986), unrelated to the orbital phase and with high spin-up rates, (ii) transients characterized by periodic outbursts of relatively high luminosity ($L_x \approx 10^{36}$ – 10^{37} erg s⁻¹; Type I) generally occurring at periastron passage of the NS, and (iii) sources which do not display outbursts, but are moderately variable (of a factor

up to 10–100) and show a low luminosity ($L_x \leq 10^{36}$ erg s⁻¹) pulsed persistent emission (Negueruela 1998).

Be stars are early type stars, with mass in the range of 2–20 M_\odot and luminosity class III to V, which often display Balmer lines in emission in their optical spectra. These stars are characterized by high rotational velocity (up to ~70% of their break-up velocity), and by phenomena of equatorial mass ejection at irregular times that give rise to a rotational-dominated quasi-Keplerian decretion disc (Hanaschik 1996; Porter 1999; Okazaki 2001; Okazaki & Negueruela 2001). The widely accepted empirical model interprets the X-ray emission from these systems, in the three mentioned behaviours, as due to sporadic mass accretion of the NS during the expansion phase of the Be disc, or to periodic close encounters of the NS in highly eccentric orbit with the dense circumstellar envelope around the Be star.

At optical wavelengths these stars are difficult to classify owing to the presence of emissions lines produced by the circumstellar envelope and to the high absorption column that affect systems lying in the Galactic plane. So far only about

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~30 optical counterparts of BeXRB's have been discovered out of the >100 known and 10^4 – 10^5 expected (Nelson et al. 1993, 1995; Covino et al. 2000; Covino et al. 2001; Israel et al. 2000a; Israel et al. 2000b; Israel et al. 2001; Chakrabarty et al. 2002).

The hard X-ray transient source XTE J1946+274 was discovered with the All Sky Monitor (ASM) on board the *Rossi* XTE satellite during a scan of the Vul–Cyg region on 1998 September 5 (Smith & Takeshima 1998). XTE J1946+274 lies inside the error box of the Ariel V transient 3A 1942+274 discovered in the 1976 (Warwick et al. 1981). Campana et al. (1999) have estimated a chance probability of ~7% that XTE J1946+274 and 3A 1942+274 are not the same source (assuming ~1000 hard X-ray transients in the Galaxy). The observed flux raised from ~13 mCrab (2–12 keV) on September 5 to ~60 mCrab on September 15, to ~110 mCrab on September 16 (in 2–60 keV; Smith & Takeshima 1998). Further observations carried out by BATSE (Wilson et al. 1998) led to the detection of X-ray pulsations with a period of 15.83 ± 0.02 s, later confirmed through pointed *Rossi* XTE/PCA observations (Smith & Takeshima 1998). A study of the lightcurve of RXTE/ASM has revealed an ~80 d (or 160 d) X-ray modulation, interpreted as orbital modulation (Campana et al. 1999).

The 1998 outburst was also monitored through a *BeppoSAX* campaign (Campana et al. 1998) which revealed a complex pulse profile (in 1–10 keV) and a complex continuum spectrum, with an iron line at 6.6 keV and an inferred column density of $\sim 1.6 \times 10^{22} \text{ cm}^{-2}$. Using *Rossi* XTE data, a cyclotron line has been detected at ~35 keV with a FWHM of ~8 keV (Heindl et al. 2001), implying a magnetic field strength of about $3.1(1+z) \times 10^{12}$ G, where z is the gravitational redshift of the scattering region.

In this paper we report on the identification of the optical/IR counterpart of XTE J1946+274 with a $R \sim 15$, Be spectral-type star. Based on *BeppoSAX* observations (circular uncertainty region with a radius of $40''$), we detected a reddened ($V - R = 1.6$) star, showing in the optical spectrum a strong $H\alpha$ emission line. The field of XTE J1946+274 has been subsequently observed in the IR band. The candidate counterpart resulted as the second brightest object in the *BeppoSAX* error circle ($H \sim 12$ mag), while the detection of Brackett $H\gamma$ emission lines in the IR spectra confirmed the Be spectral classification of the star. A recently refined *BeppoSAX* error circle ($22''$ of radius) has finally confirmed the identification ruling out the possible link between the X-ray transient pulsar and the brightest IR source included in the previous *BeppoSAX* uncertainty region.

2. The X-ray position

The positional uncertainty region obtained with the *Rossi* XTE/PCA is a circle with a radius of $2'.4$ (90% confidence level; Takeshima & Chakrabarty 1998); the latter was reduced with *BeppoSAX* Narrow Field Instruments pointed observations to $40''$ (90% confidence level; Campana et al. 1998). The *BeppoSAX* X-ray position was $RA = 19^h45^m38^s$, $Dec = +27^\circ21'5''$ (equinox 2000.0). This position could be refined thanks to a detailed study performed on

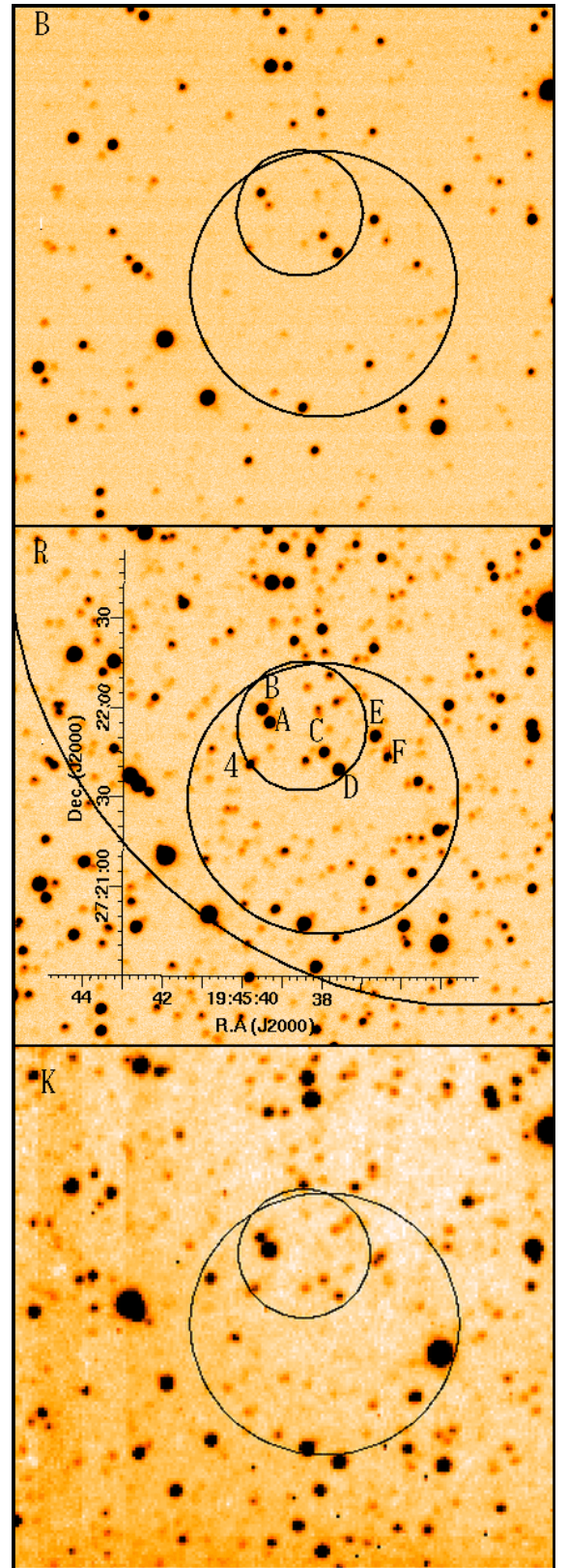


Fig. 1. Optical *B*, *R*-filter (upper panels) and IR *K*-filter (lower panel) images of the field of XTE J1946+274 together with the X-ray position uncertainty circles derived from *BeppoSAX* (inner circles) and *Rossi* XTE (larger circle in the *R*-filter image) observations; RA (h m s) and Dec ($^\circ$ ' ") coordinates are shown in the central panel (equinox J2000). The object marked with A is the proposed optical counterpart.

Table 1. Optical/IR observations carried out for the field of XTE J1946+274.

Telescope & Instrument	Date	Exp. (s)	Seeing ($''$)	Range/Slit ($\text{\AA}/''$)	Candidate	Cand. A $H\alpha$ EW (\AA)
1.5 m Cassini & BFOSC	1999 July 11	2400	2.5	4000–9000/2.5	C,D	–
–	1999 July 12	150	1.9	<i>V</i>	–	–
–	–	300	–	<i>B</i>	–	–
–	–	100	–	<i>R</i>	–	–
–	–	60	–	<i>I</i>	–	–
–	–	1800	–	4000–9000/2.5	B,A	-39 ± 7
–	1999 July 13	2400	3.3	4000–9000/2.5	E,F	–
–	–	1800	–	–	B,A	-38 ± 7
–	1999 July 14	2400	2.0	4000–9000/2.0	4	–
–	–	5400	–	–	A	-40 ± 10
–	1999 July 15	2400	2.6	4000–9000/2.5	A	-40 ± 12
–	1999 July 16	4500	2.0	3300–5800/2.5	A	–
–	1999 July 17	2700	1.6	–	A	–
–	1999 July 19	2700	1.5	5800–8300/2.5	A	-42 ± 3
–	–	2700	–	5800–8300/2.0	A	-40 ± 4
–	–	1800	–	4000–9000/2.5	A	-45 ± 8
3.8 m UKIRT & CGS4	1999 July 24	300	1.5	20 400–22 000/1.0	A	–
1.1 m AZT–24 & SWIRCAM	1999 July 27	60	2.1	<i>J</i>	–	–
–	1999 July 27	60	–	<i>H</i>	–	–
–	1999 July 27	60	–	<i>K</i>	–	–
4.2 m WHT & ISIS	2000 July 18	2400	0.9	3200–9000/1.0	A	-41.0 ± 0.5
1.5 m Cassini & BFOSC	2000 July 31	3600	2.0	5000–9500/2.5	A	-40 ± 8
–	2000 August 28	1800	3.0	4000–9000/2.5	A	-33 ± 5
–	2001 June 18	3600	1.8	3600–8000/2.0	A	-40 ± 5

73 relatively bright sources with known optical position observed by *BeppoSAX* during its life (see also Fiore et al. 2001). The position uncertainty was found to depend on several factors (intensity, off-axis angle, roll angle, energy-dependent PSF, number of gyros and star-trackers, etc.) some of which can be taken properly into account ending up with a MECS error radius of $14''$ and $22''$ at 68% and 90% confidence level, respectively. The first *BeppoSAX* position was then corrected for these systematic uncertainties by performing a simple boresight correction: the final XTE J1946+274 position is RA = $19^{\text{h}}45^{\text{m}}38^{\text{s}}.5$, Dec = $+27^{\circ}21'54''.3$ (radius of $22''$ at 90% confidence level, equinox 2000.0).

3. Optical/IR observations

We carried out observations in the optical and IR band of the *BeppoSAX* error circle in several observing periods during 1999–2001 (see Table 1) at the Loiano observing station (Bologna Observatory), at Campo Imperatore (Observatory of Rome), at the United Kingdom Infrared Telescope (UKIRT, Mauna Kea, Hawaii) and at the William Herschel Telescope (WHT, La Palma, Spain).

3.1. Imaging

On July 1999 we performed imaging and photometry in the *B* (300 s), *V* (150 s), *R* (100 s) and *I* (60 s) filters with the 1.5-m Cassini telescope equipped with the Bologna Faint Objects Spectrometer and Camera (BFOSC; Bregoli et al. 1987; Merighi et al. 1994; 12.2×12.2 field of view and

$0''.58/\text{pixel}$ resolution, and a maximum resolution of ~ 900 in the 3500–9000 \AA range with a $1''.0$ slit). Data reduction was performed using standard ESO–MIDAS procedures for bias subtraction and flat-field correction. Aperture and profile-fitting photometry for each stellar object in the image was derived with the DAOPHOT II program (Stetson 1987).

We performed astrometry of the field using the USNO catalog, resulting in a better than $0''.4$ positional accuracy. The same field was observed in the IR *J* (60 s), *H* (60 s) and *K* (60 s) filters on July 1999 with the 1.1-m AZT–24 telescope equipped with the Supernova Watchdogging IR Camera (SWIRCAM; 4.4×4.4 field of view and $1''.04/\text{pixel}$ resolution). Similar analysis procedures were applied to IR data.

Figure 1 shows the *B*, *R* and *K*-filter images of the field which includes the XTE J1946+274 position: the 90% position uncertainty circles as inferred by *Rossi* XTE (the largest one in the *R*-filter image) and *BeppoSAX* (the inner circles) are also shown.

Within the refined *BeppoSAX* X-ray positional error circle we detected seven relatively bright (see Fig. 1) stars among which only one (labeled as A) was a reddened ($V - R = 1.6$, all others had $V - R < 1$) and relatively bright IR object ($H = 12.1$). In Table 2 we list results of optical/IR photometry for all seven stars.

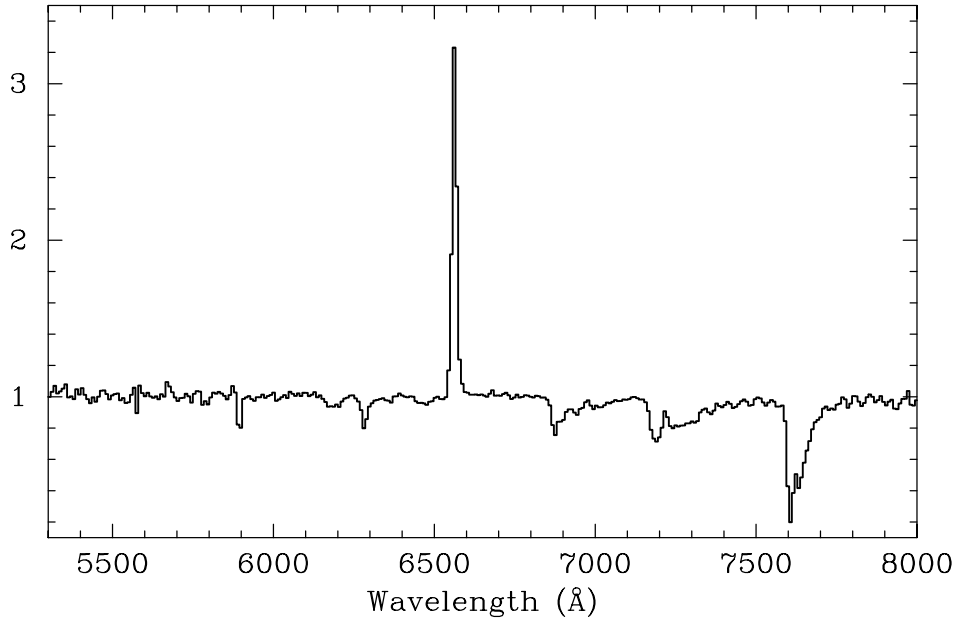
3.2. Optical spectroscopy

During July 1999 we also performed low-resolution ($\sim 18 \text{\AA}$) spectroscopy of all relatively bright stars within the refined *BeppoSAX* circle (see Table 1). We applied standard

Table 2. Optical and IR results for the objects in the *BeppoSAX* error circle. Object A is the proposed counterpart.

Object	<i>B</i> (± 0.05)	<i>V</i>	<i>R</i> (± 0.03)	<i>I</i> (± 0.02)	<i>V - R</i>	<i>J</i> (± 0.1)	<i>H</i> (± 0.1)	<i>K</i> (± 0.1)	<i>J - H</i>
A	18.62	16.90 ± 0.03	15.32	13.32	1.58	12.7	12.1	11.6	0.6
B	17.29	15.53 ± 0.03	15.13	13.74	0.94	13.9	13.3	13.2	0.6
C	17.71	16.54 ± 0.04	15.68	14.37	0.86	14.7	14.2	14.1	0.5
D	16.71	15.71 ± 0.03	14.96	13.76	0.75	14.3	13.9	14.0	0.4
E	17.15	16.06 ± 0.03	15.33	14.08	0.73	14.5	13.9	13.8	0.6
F	18.89	17.33 ± 0.04	16.50	15.16	0.83	15.7	15.2	15.1	0.5
4	18.94	17.56 ± 0.03	16.66	15.22	0.90	–	–	–	–
RA(J2000) =	19 ^h 45 ^m 39 ^s .3								
Dec(J2000) =	+27°21′55″.4								
Spectral type:	B0–B1 IV–V e								
E_{B-V} :	1.9 \rightarrow 2.2								
Distance:	~8–10 kpc								

Note – Photometric uncertainties are at 3-sigma confidence level. Position uncertainty is 0′.4.

**Fig. 2.** The 3600-s low resolution (18 Å) spectrum of XTE J1946+274 candidate A (see Fig. 1 middle panel) obtained on 2000 July 31 from the 1.5 m Cassini telescope at Loiano (Bologna, Italy).

corrections to spectra, i.e. one-dimensional stellar and sky spectra extraction, then removed cosmic rays and, when weather condition were satisfactory, we performed absolute calibration both for spectroscopy and photometry.

All the spectra carried out in July 1999 in the 4000–9000 Å band (with different slit apertures) were rebinned to the largest resolution, 18.4 Å, and then summed to increase the S/N ratio. None of the objects showed emission lines except star A. For the latter source we detected a strong emission line (equivalent width, EW , of -43 ± 5 Å and Full Width Half Maximum, FWHM, comparable with the spectral resolution) with central wavelength corresponding to that of $H\alpha$ (see e.g. Fig. 2 for a 5000–9500 Å spectrum of star A obtained during a 3600 s observation performed on 2000 July 31). Similarly we reduced, rebinned (9 Å of resolution) and summed two spectra of star A in the band 5800–8300 Å to better characterize the $H\alpha$ emission line ($EW -42 \pm 2$ Å).

Spectra for star A were subsequently carried out routinely during several 2000–2001 observational nights to study the possible presence of variations of emission line parameters. The $H\alpha$ EW s are consistent with being constant during our observations (see Table 1). Owing to the faintness of the source shortwards of 5000 Å, no emission lines have been detected in the blue part of spectra, with the exception of a possible emission ($EW -6.0 \pm 0.3$ Å) corresponding to $H\beta$.

Finally, on 2000 July 18 two 1200-s medium-resolution spectra were taken with the Intermediate Dispersion Spectroscopic and Imaging System (ISIS) mounted on the 4.2 m William Herschel Telescope (WHT), located at the Observatorio del Roque de los Muchachos, (La Palma, Spain). The blue arm was equipped with the R300B grating and the EEV#10 CCD, which gives a nominal dispersion of ~ 0.9 Å/pixel. The resolution at $H\alpha$, estimated from the FWHM of arc lines, is ~ 3.3 Å. The red arm was equipped

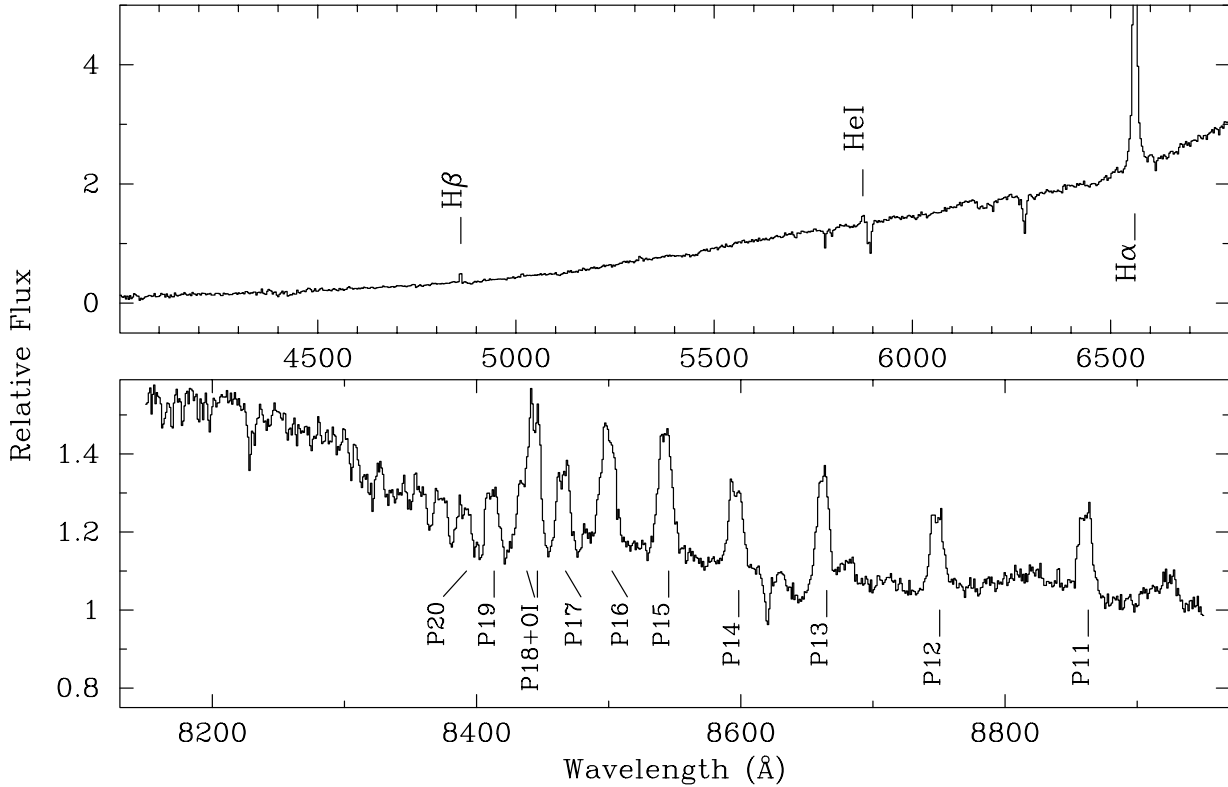


Fig. 3. The 2400-s spectrum (3.3 Å and 1.6 Å spectral resolution in the 4000–7000 Å and 8000–9000 Å range, respectively) of XTE J1946+274 candidate A obtained on 2000 July 18 from the 4.2 m William Herschel Telescope at Roque de los Muchachos (La Palma, Spain). Balmer, Paschen and helium series lines are indicated.

with the R600R grating and the Tek4 CCD, which gives a nominal dispersion of ~ 0.8 Å/pixel (the resolution is ~ 1.6 Å at $\lambda \sim 8500$ Å). The blue part of the spectrum is dominated by strong diffuse absorption bands (see Fig. 3). The only feature clearly recognizable shortwards of H β (which is clearly in emission with EW of -2.0 ± 0.5 Å) is the $\lambda 4430$ Å DIB. An exact spectral classification is therefore impossible. However, based on the usual properties of Be stars, we can strongly constrain the spectral type. The presence of He I $\lambda 5875$ Å strongly in emission is only observed in the earliest Be stars (earlier than B2). Likewise, the presence of strong emission in the Paschen series (labelled with P in the lower panel of Fig. 3) confirms that the object is earlier than B2 (Andrillat et al. 1988). As the lack of a detectable He II $\lambda 5412$ Å absorption line imposes a spectral type later than O9.5, the object is constrained to lie in the B0–B1 range. This is within the spectral range occupied by known Galactic and LMC Be/X-ray binary counterparts, which have spectral types tightly concentrated around B0 (Negueruela & Coe 2002).

3.3. IR spectroscopy

Spectroscopic IR observations of XTE J1946+274 candidate were made with the United Kingdom Infrared Telescope (UKIRT; Joint Astronomy Centre, Mauna Kea, Hawaii) on 1999 July 24, using the Cooled Grating Spectrometer (CGS4). Observations between 2.04–2.2 microns were made using the long focal length camera plus the 150 line/mm grating,

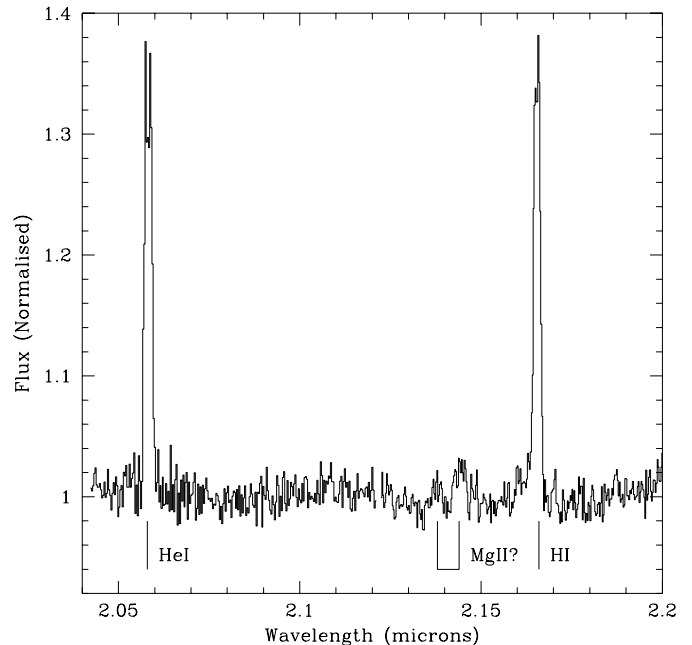


Fig. 4. The 300-s IR spectrum of XTE J1946+274 candidate A obtained on 1999 July 24 from the UKIRT (Mauna Kea, Hawaii).

giving a velocity resolution of ~ 50 km s $^{-1}$. Initial data reduction was carried out at the telescope using the CGS4DR software (Puxley et al. 1992). This removes bad pixels, debiases, flat-fields, linearity corrects and interleaves oversampled scan

positions. The subsequent stages of data reduction, comprising of sky subtraction, extraction, derippling and wavelength calibration, were carried out using the Starlink-supported package FIGARO. Removal of telluric features was accomplished via the procedure described by Clark & Steele (2000).

The spectrum (see Fig. 4) shows strong emission from He I 2.058 μm ($EW = -8.1 \pm 0.4$ Å) and H I Bracket γ ($EW = -8.0 \pm 0.4$ Å). FWHMs for the two lines are identical within the errors on the measurements and yield a mean value of 300 ± 50 km s⁻¹. There is some evidence for weak emission in the Mg II 2.138/2.144 μm doublet ($EW = -0.6 \pm 0.4$ Å and -1.4 ± 0.4 Å, respectively), although further higher S/N observations are required to confirm this. If the emission features are real the ratio of the EW of both lines suggests that the lines are optically thin, and are expected to be excited via Ly β fluorescence. No evidence for emission from Fe II 2.189 μm or He I 2.112/3 μm emission or absorption was found.

Comparison to the K band spectra of classical Be stars presented by Clark & Steele (2000) suggests that XTE J1946+274 candidate A can be classified as a Group 1 object consistent with it being of early (O9–B3) spectral type (given the paucity of photospheric features in the near IR it is not possible to classify a Be star to greater accuracy than ± 2 spectral types or provide a luminosity class) in agreement with the optical spectroscopic findings. We find no anomalous emission from higher excitation species to suggest that the star has a compact companion; in line with the trend displayed by other Be/X-ray binaries for which K band spectra have been obtained which also have spectra indistinguishable from those of isolated early spectral type classical Be stars (e.g. Clark et al. 1999).

4. Discussion and conclusion

We have presented the X-ray, optical and IR observational data of the field containing the error circle of XTE J1946+274; these observations led to the likely identification of the optical counterpart of this 15.8-s transient X-ray pulsar. Optical/IR photometric measurements are consistent with a relatively reddened and distant blue star, similar to known optical/IR counterparts of BeXRBs (see Nelson et al. 1993, 1995; Israel et al. 2000a; Israel et al. 2000b; Covino et al. 2000; Covino et al. 2001; Israel et al. 2001; Chakrabarty et al. 2002).

Owing to the uncertainty in the spectral classification, the measurement of the distance from optical data becomes difficult; it is however possible to extract some information from our optical and IR data. The observed $V - R$ color for XTE J1946+274 is ~ 1.6 , while the intrinsic one should be $\sim -0.14 \rightarrow -0.11$ (assuming a main sequence or sub-giant star with spectral class in the B0–B1 III–V range; Wegner 1994), so the reddening should amount to $\sim 1.7 \rightarrow 1.8$. Assuming a standard reddening law (Fitzpatrick 1999) this converts to $A_R \sim 5.0 \rightarrow 5.1$, $A_V \sim 6.7 \rightarrow 6.8$ and $E_{B-V} \sim 2.0 \rightarrow 2.2$ (regardless of the distribution of the medium responsible for the reddening along the line of sight and near the source, i.e. assuming that the reddening due to circumstellar disk is negligible).

However from the X-ray spectral data (Campana et al. 1998) a N_H of $\sim 1.6 \times 10^{22}$ cm⁻² was inferred, corresponding

to an $E_{B-V} \sim 2.9$ (Predehl & Schmitt 1995), which is slightly more than what obtained from optical data. Considering the total Galaxy N_H column in the direction of XTE J1946+274 (Dickey & Lockman 1990), $< 1 \times 10^{22}$ cm⁻², a value of $E_{B-V} \sim 1.9 \rightarrow 2.1$ was inferred, which comfortably overlaps the value inferred from the optical data. This result suggests that at least part of the inferred X-ray N_H is local to the system and obscures the neutron star during outbursts. A good agreement with the B to I measurements is obtained for a B0–1IV–V star at a distance of about 8–10 kpc and with $E_{B-V} \sim 2$ (see Table 2). We can reasonably discard the possibility of a luminosity class III which would imply an $E_{B-V} > 2.3$ and a large IR-deficiency. For a reference B0–1IV–V star ($M_V \sim -3.5$) at a distance of 8–10 kpc and based on the IR photometry we infer an excess of ~ 0.4 , 0.5 and 1.4 mag in J , H and K filters respectively, suggesting the presence of a circumstellar envelope. Finally we note that in the direction of XTE J1946+274 there are two spiral arms of our Galaxy located at ~ 4 kpc and ~ 9 kpc away from the Earth (Perseus and Cygnus arms; Turner 1980; Taylor & Cordes 1993; Vallée 2002), so XTE J1946+274 could belong to the second one. Moreover this distance estimation is very similar to that found for the nearby source KS 1947+300 (Negueruela et al. 2002), which could lie on the same arm.

For a distance of 8–10 kpc and a 1–10 keV flux of $\sim 1 \times 10^{-9}$ erg s⁻¹ cm⁻² at the peak of the 1998 outburst (Takeshima & Chakrabarty 1998) we obtain an X-ray luminosity of L_X (1–10 keV) $\simeq 8\text{--}20 \times 10^{36}$ erg s⁻¹. Such a luminosity is a typical value shown by X-ray pulsars in binary systems during Type I outbursts (Stella et al. 1986; Negueruela 1998) occurring close to the time of periastron passage and with a periodic recurrence at the orbital period of the system.

Based on both X-ray and optical/IR observations we identify the likely optical/IR counterpart of XTE J1946+274. Moreover, photometric and spectroscopic optical/IR data allows us to conclude that the proposed optical counterpart is most likely a B0–1 V–IVe star at a distance of about $\sim 8\text{--}10$ kpc. A more accurate distance and spectral classification would require more detailed optical/IR spectroscopic observations.

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